5th TLEP Workshop

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Top precision measurements at LC - Theory improvements

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Top quark physics at TLEP

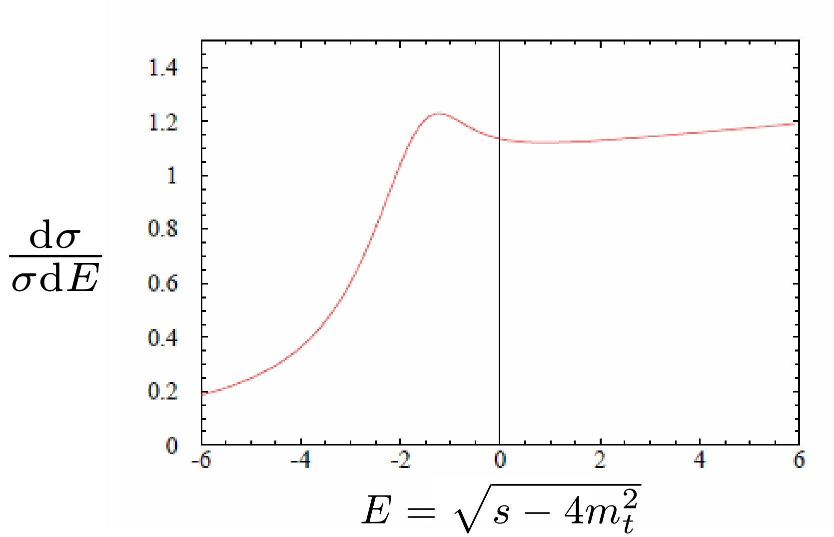
- TLEP at E=350 GeV gives us the opportunity to study ttbar production around its threshold.
- The high luminosity and the clean experimental environment at TLEP promise a high precision top quark physics program.
- High precision might be a next logical step if no striking discoveries show up at the LHC, or if a discovery requires further scrutiny.
- Of course, this has to be seen in perspecive with prospects for ILC/CLIC and the LHC. First studies indicate that TLEP performance is competitive. + It offers a long term vision for HEP in Europe.

Outline

- **Threshold scan**
  ttbar cross section
  Top quark mass, width
- **Top quark couplings**
  Electroweak couplings
  Yukawa coupling
  Rare decays, FCNC, single top
- **Light stops**

Threshold scan

Threshold scan

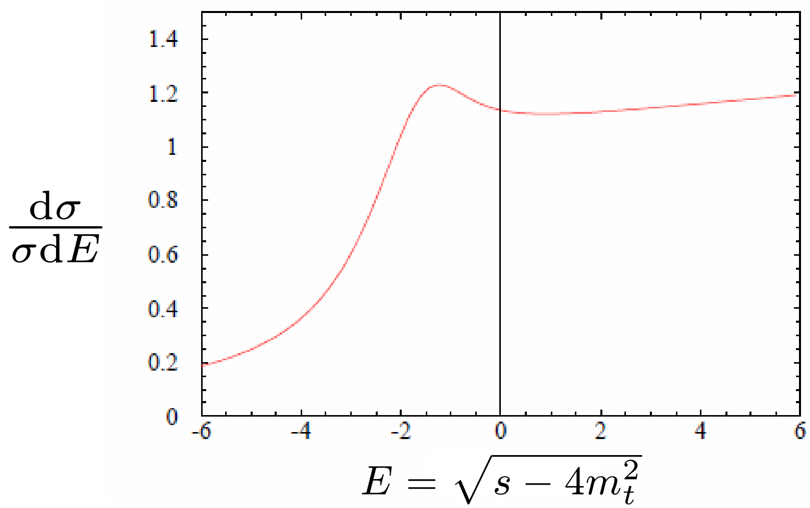


- The Rydberg binding energy of toponium $\sim m_t \alpha_s^2 \approx 2\ \mathrm{GeV}$ is similar to the top quark width $\Gamma_t \approx 1.5\ \mathrm{GeV}$, both of which are much larger than Λ_{QCD}.

→ Two opposite effects govern the top quark threshold region:

- The QCD interaction between the non-relativistic top quarks pulls towards Coulomb-like toponium bound states.
- The large top quark width $\Gamma_t \gg \Lambda_{\mathrm{QCD}}$ leads to a rapid decay before a bound state can be formed.

Threshold scan



- The resonance peak is smeared out.

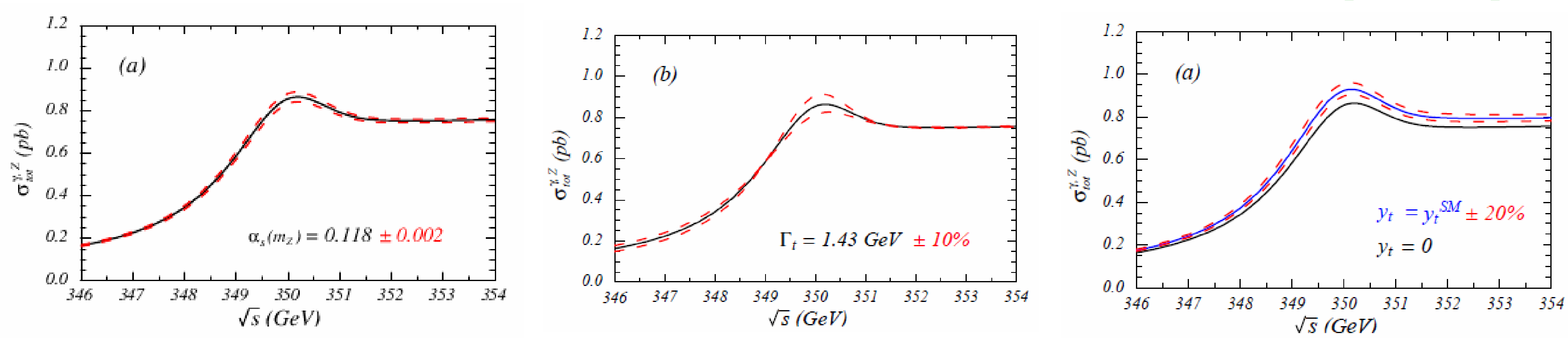
- The large decay width effectively serves as a cut-off for non-perturbative effects → cross section can be described within perturbation theory.

- The slow velocity close to threshold requires a pert. expansion in α_s^n / v^m → NRQCD with QCD Coulomb potential.

→ This allows a reliable description of the threshold region which is based entirely on first principles.

Threshold scan

[Stewart]



- The resonance cross section $\sigma_{\rm res} \sim \alpha_s^3/(m_t\Gamma_t)$ is very sensitive to strong coupling, top quark mass and width.

- Higgs boson exchange introduces dependence on y_t through loops.

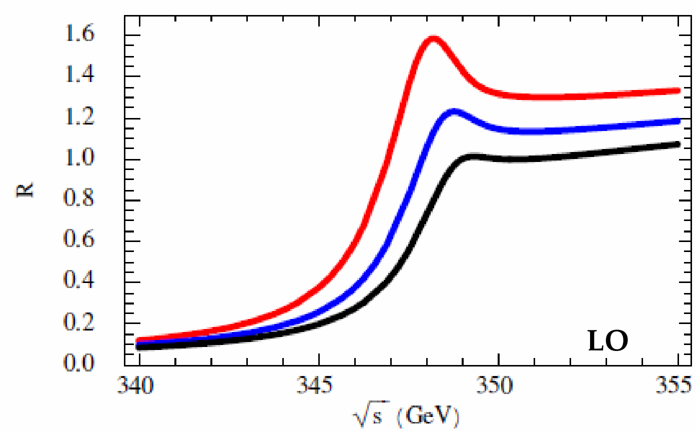
→ To what precision can we predict threshold dynamics? What is the expected experimental sensitivity?

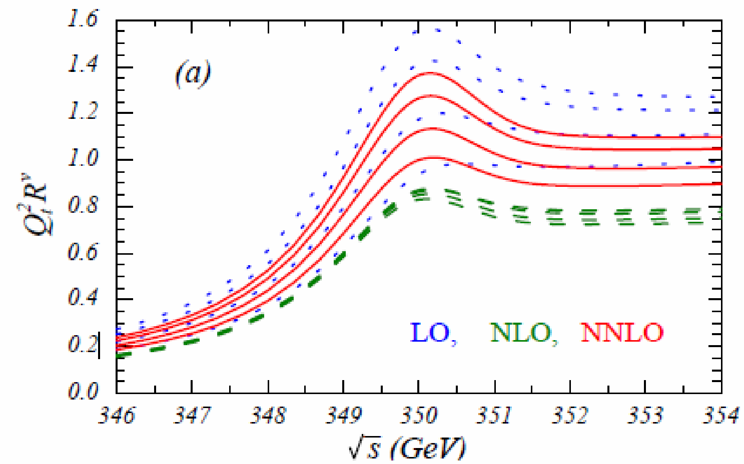
Threshold scan: the ttb cross section

Coulomb resummation

$$R = \frac{\sigma_{t\bar{t}}}{\sigma_{\mu^+\mu^-}} = v \sum_k \left(\frac{\alpha_s}{v}\right)^k \times \Big[1 + \{\alpha_s, v\} + \{\alpha_s^2, \alpha_s v, v^2\} + \ldots \Big]$$

LO NLO NNLO

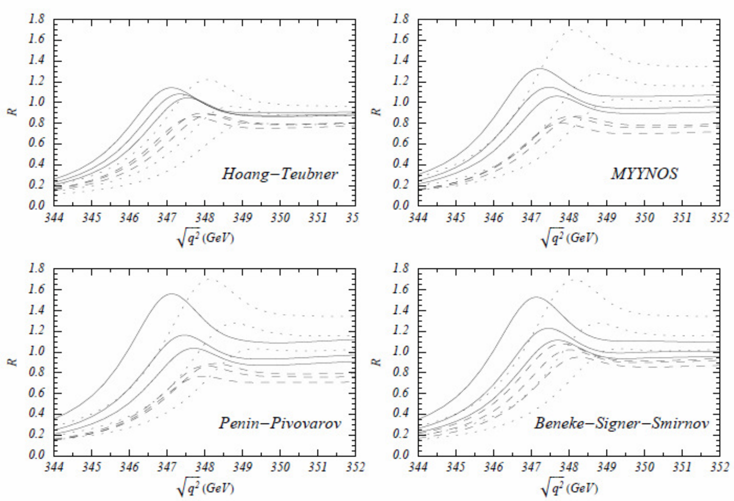




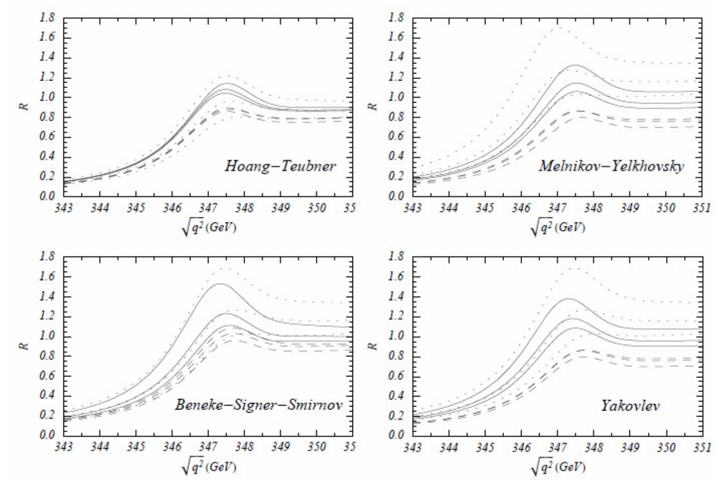
- Description pushed to NNLO by several groups:
  [Hoang,Beneke, Melnikov,Nagano, Ota, Penin,Pivovarov, Signer,Smirnov,Sumino,Teubner,Yakovlev,Yelkhovsky]
- Corrections are large, scale variation bands do not overlap
  residual scale uncertainty ~ 20 %
  → partly contributed to Renormalon contribution of
  top quark pole mass, logs of largly different scales (E_t - v_t - m_t)

Threshold scan: the ttb cross section

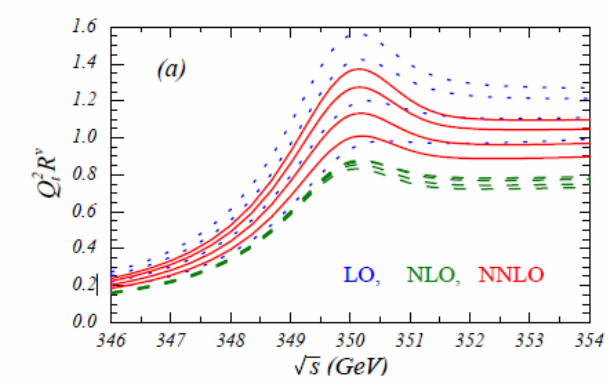
- More appropriate „short-distance“ definitions of top quark mass such as MSbar or threshold mass improve convergence:



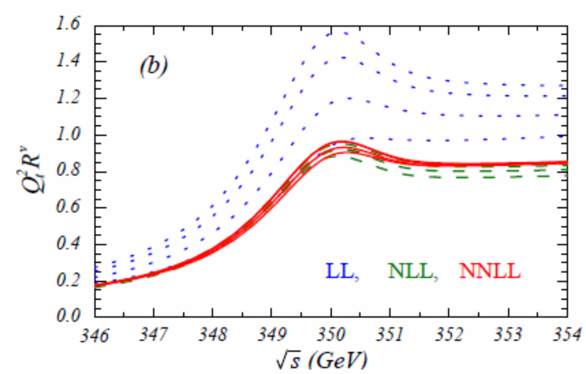
short dist. masses



- Logarithmic resummation: $R = \mathrm{v} \sum_k \left(\frac{\alpha_s}{\mathrm{v}}\right)^k \sum_j (\alpha_s \ln \mathrm{v})^j \times \left[1 + \{\alpha_s, \mathrm{v}\} + \{\alpha_s^2, \alpha_s \mathrm{v}, \mathrm{v}^2\} + \ldots\right]$



resum logs(v)



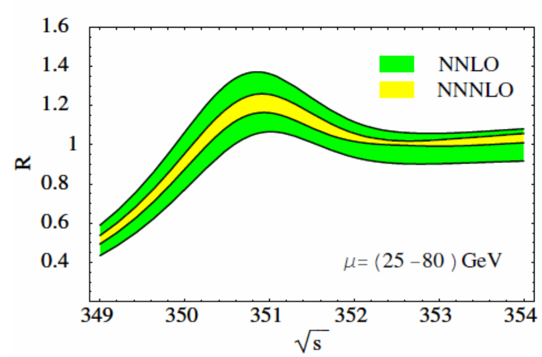
[Stewart]

Threshold scan: the ttb cross section

- **Ultimately, for a rigorous quantitative analysis of threshold production the complete N³LO corrections are required.**

- Significant progress towards this goal in recent years. We can expect the full result in the near future.

  [Anzei,Beneke,Hoang,Kiyo,Kniehl,Marquard,Penin, Piclum,Schuller,Seidel,Smirnov,Steinhauser,Sumino]



[Beneke,Schuller,Kiyo]

→ The N³LO uncertainty on total cross section is likely of order 3%.

Threshold scan: the ttb cross section

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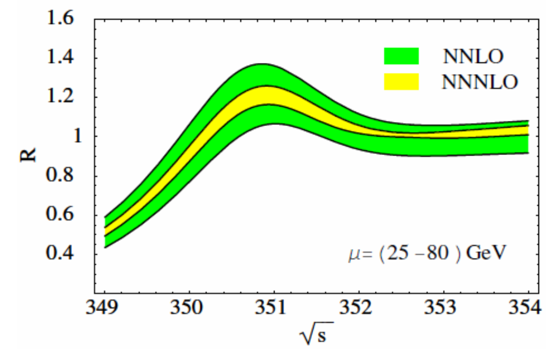


[Beneke,Schuller,Kiyo]

→ **The N³LO uncertainty on total cross section is likely of order 3%.**

- At this level of precision one needs to account for

  - electroweak corrections [Grzadkowski,Kuhn,Krawczyk,Stuart],[Hoang,Reisser]
  - mixed QCD-el.weak corrections [Eiras,Steinhauser],[Kiyo,Seidel,Steinhauser]
  - finite width effects, non-factorizable corrections [Hoang,Reisser,Femenia]

Threshold scan: the top quark mass

[Penin,Steinhauser]
[Kiyo,Sumino]

N^{3}QCD relation for resonance energy and m_t:

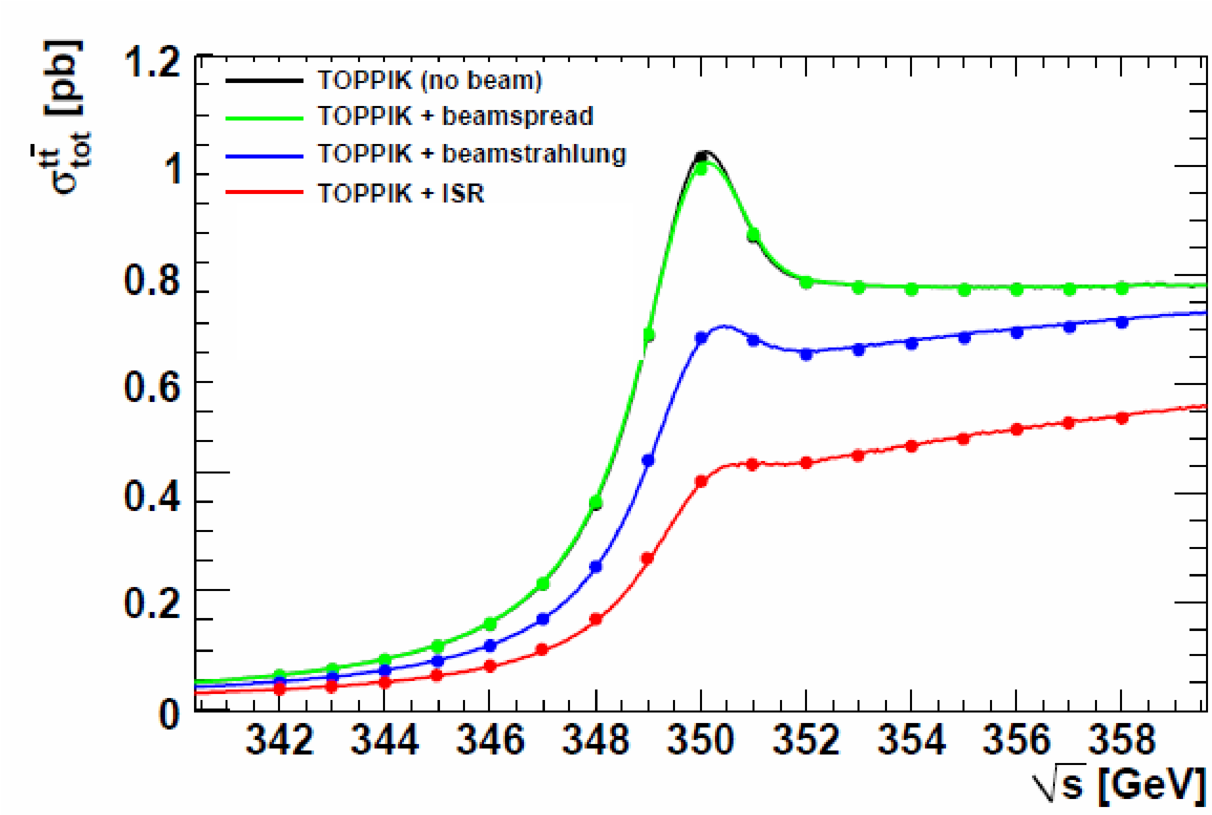
$$\sqrt{s_{\rm res}} = \left[1.9833 + 0.007\,\frac{m_t - 174.3\ \mathrm{GeV}}{174.3\ \mathrm{GeV}} \pm 0.0009\right] \times m_t\,,$$

→ Theoretical uncertainty of **80 MeV** on m_t (pole mass)

→ The use of the short-distance MSbar mass reduces uncertainty to **40 MeV**.

Threshold scan: the top quark mass

Realistic studies need to include beam and detector effects, ISR, backgrounds,...



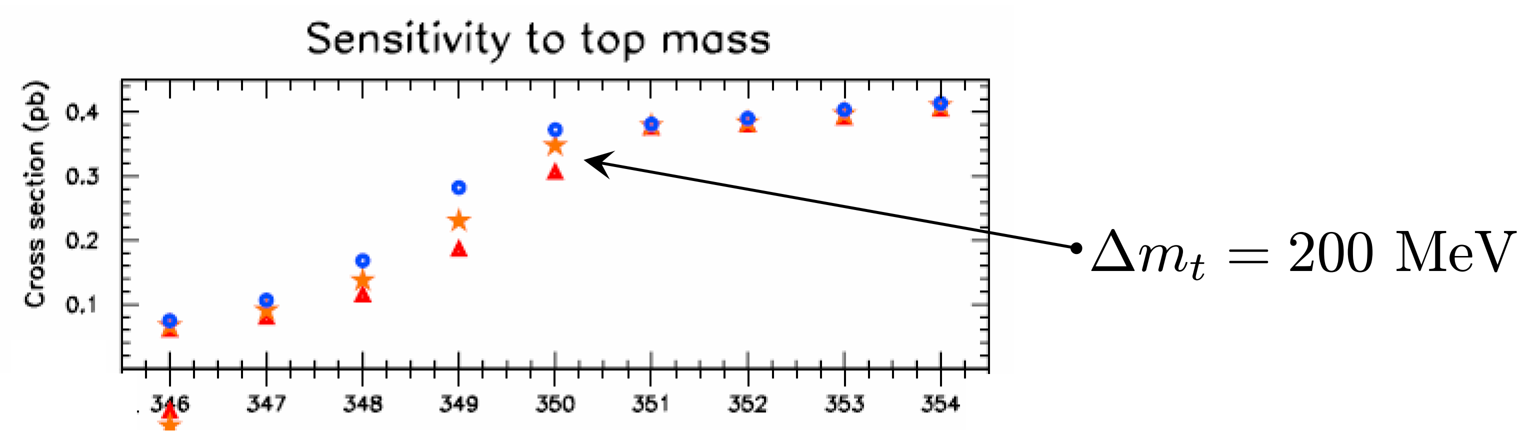
[Gournaris]

Threshold scan: the top quark mass

[Martinez,Miquel]: Multi-parameter fits to the $t\bar{t}$ threshold observables at a future e^+e^- linear collider

(Standard reference for a realistic study)

Use NNLO simulation and include detector effects, selection efficiency and backgrounds, assuming the TESLA beam and detector design.



→ The simulations show an estimated experimental error of about **3%** on the total cross section (much below the one of the differential observables).

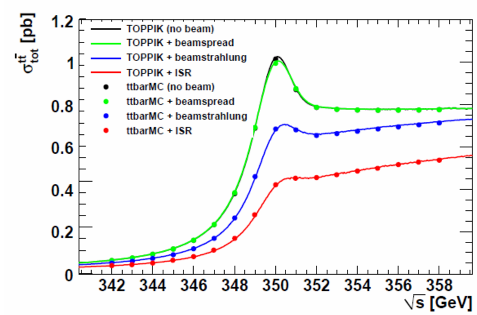
→ The resulting uncertainty on m_t is **31 MeV** (from multiparam. fit of 3 observables). *Neglecting uncertainties from beam energy and luminosity spectrum.*

Threshold scan: the top quark mass

[Martinez,Miquel]: Multi-parameter fits to the $t\bar{t}$ threshold observables at a future e^+e^- linear collider

(Standard reference for a realistic study)

[Gournaris]: Similar study for ILC including beam and luminosity uncertainties



→ In summary, for a 300 fb^{-1} threshold scan the total expected uncertainty on m_t **is 100 MeV**, resulting from the sum in quadrature of the following contributions:

31 MeV ([Martinez,Miquel]),

35 MeV (beam energy),

50 MeV (luminosity spectrum) and

80 MeV (from the conversion of s_{res} into m_t).

Above threshold: the top quark mass

$\delta m_t = 100$ MeV in perspective:

- **LHC projections:** [Snowmass]

	Projections				
CM Energy	14 TeV				
Luminosity	$100 fb^{-1}$		$300 fb^{-1}$		$3000 fb^{-1}$
Syst. (GeV)	0.7	0.7	0.6	0.6	0.6
Stat. (GeV)	0.04	0.04	0.03	0.03	0.01
Total, GeV	**0.7**	**0.7**	**0.6**	**0.6**	**0.6**

likelihood methods

Projections		
14 TeV		
$100 fb^{-1}$	$300 fb^{-1}$	$3000 fb^{-1}$
1.0	0.7	0.5
0.10	0.05	0.02
1.0	**0.7**	**0.5**

kinem. end-points

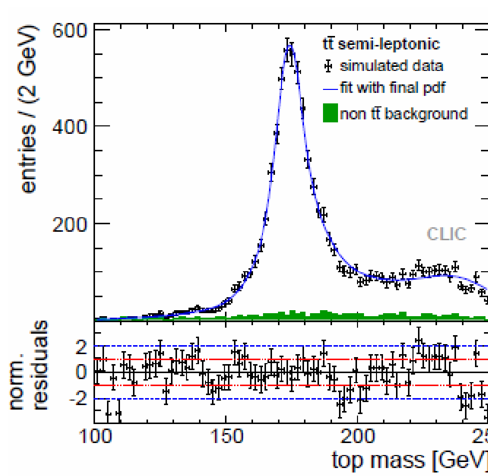
Projections				
14 TeV			33 TeV	100 TeV
$100 fb^{-1}$	$300 fb^{-1}$	$3000 fb^{-1}$	$3000 fb^{-1}$	$3000 fb^{-1}$
1.5	1.5	1.0	1.0	0.6
1.8	1.0	0.3	0.1	0.1
2.3	**1.8**	**1.1**	**1.0**	**0.6**

J/Psi method

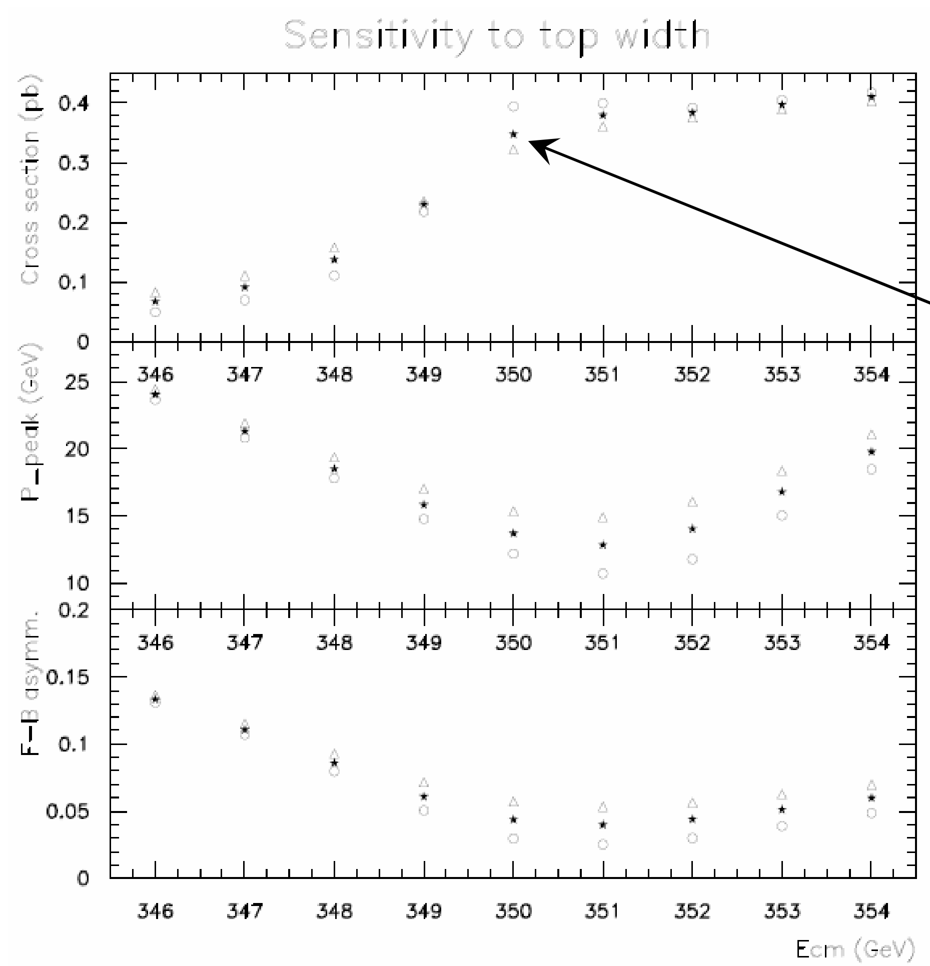
- **ILC/CLIC projections:** [Seidel,Simon,Tesar]

channel	m_{top}	Δm_{top}	σ_{top}	$\Delta\sigma_{top}$
fully-hadronic	174.049	0.099	1.47	0.27
semi-leptonic	174.293	0.137	1.70	0.40
combined	174.133	0.080	1.55	0.22

Table 2 Results summary for the top mass measurement at 500 GeV for an integrated luminosity of 100 fb^{-1}. All numbers are given in units of GeV. Errors are statistical only.



Threshold scan: top quark width



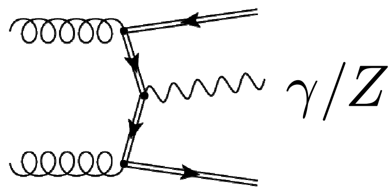
[Martinez,Miquel]

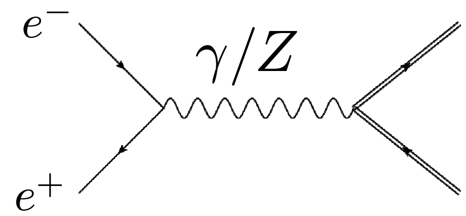
$$\Delta\Gamma_t = 400 \text{ MeV}$$

- Accuracy of 2% on top quark width is achievable

Top quark couplings

Top quark electroweak couplings





$$\Gamma_\mu^{t\bar{t}V} \sim \gamma_\mu \left(F_{1,V} + \gamma_5 F_{1,A}\right) + \sigma_{\mu\nu} \frac{q^\nu}{2m_t} \left(\mathrm{i}F_{2,V} + \gamma_5 F_{2,A}\right)$$

- Currently, these couplings are not very well measured (apart from Q_t).
  At hadron colliders only accessible through ttb+γ and ttb+Z.
  At Tevatron, a handful of ttb+γ events. Indirect constraints from CLEO,LEP on ttbZ.
  → Ultimate precision at the LHC (3000 fb^{-1}): **10-20%** [Baur,Juste,Orr,Rainwater]

- In e+e- collisions, the cross section has an entangled dependence on photon and Z coupling. Polarized beams and FB asymmetries can be used to get a handle on individual couplings. [ILC TDR], [Devetak,Nomerotski,Peskin]
  → ILC precision with 500 fb^{-1}: **sub percent level** (80:30% polarization)
  [Baur et al.], [Snowmass reports]

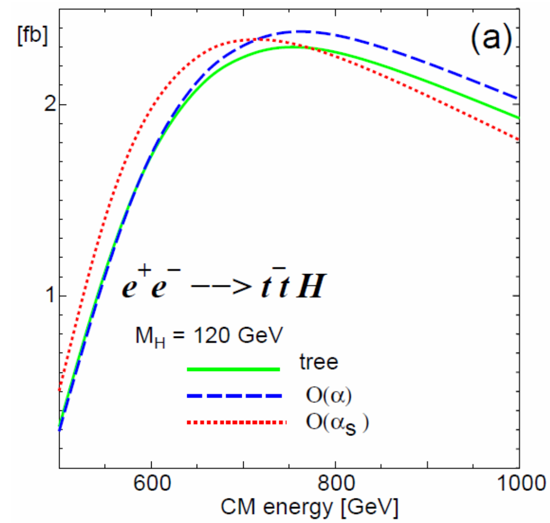
- At TLEP, only vector part accessible (axial couplings require p-wave)
  → no sensitivity to electric dipole moments
  most likely compatible with ILC precision (higher lumi but no polarization)

Top quark Yukawa coupling

$$e^+e^- \to t\bar{t} + H$$

- $E_{\rm thresh} = 2^* m_t + m_H = 470$ GeV

  → large gain from increased CM energy
  $\sigma(800\ \text{GeV})/\sigma(500\ \text{GeV}) \sim 7$



$$\sqrt{s} = 500\ \text{GeV},\ \mathcal{L} = 1000\text{fb}^{-1}:\ \delta y_t/y_t \approx 10\%$$

[Dawson,Juste,Reina,Wackeroth]

$$\sqrt{s} = 800\ \text{GeV},\ \mathcal{L} = 1000\text{fb}^{-1}:\ \delta y_t/y_t \approx 6\ \%$$

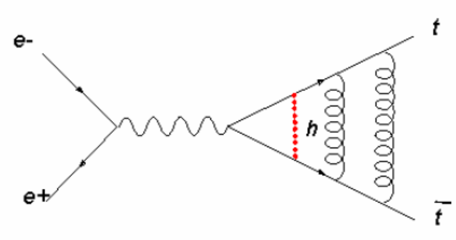
[Yonamine,Ikematsu,Tanabe, Fujii,Kiyo,Sumino,Yokoya]

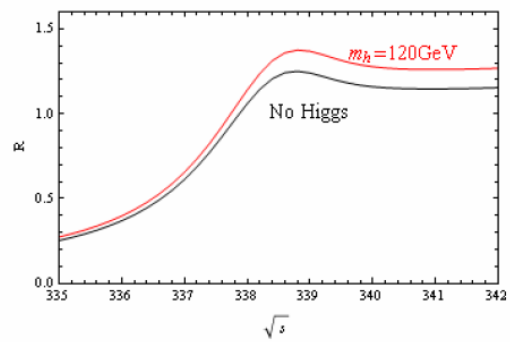
- At the LHC, difficult final state with huge background.
  Still, 15-20 % precision seems possible.

[CMS-NOTE-2012-006], [ATLAS-PHYS-PUB-2012-004]

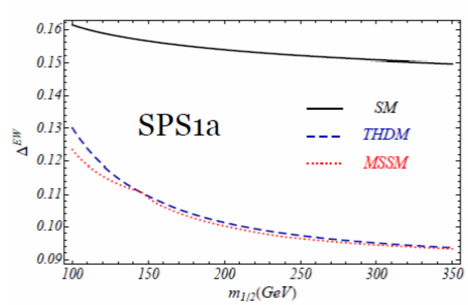
Threshold scan: Top quark Yukawa coupling

- At TLEP energies, sensitivity only through loop effects



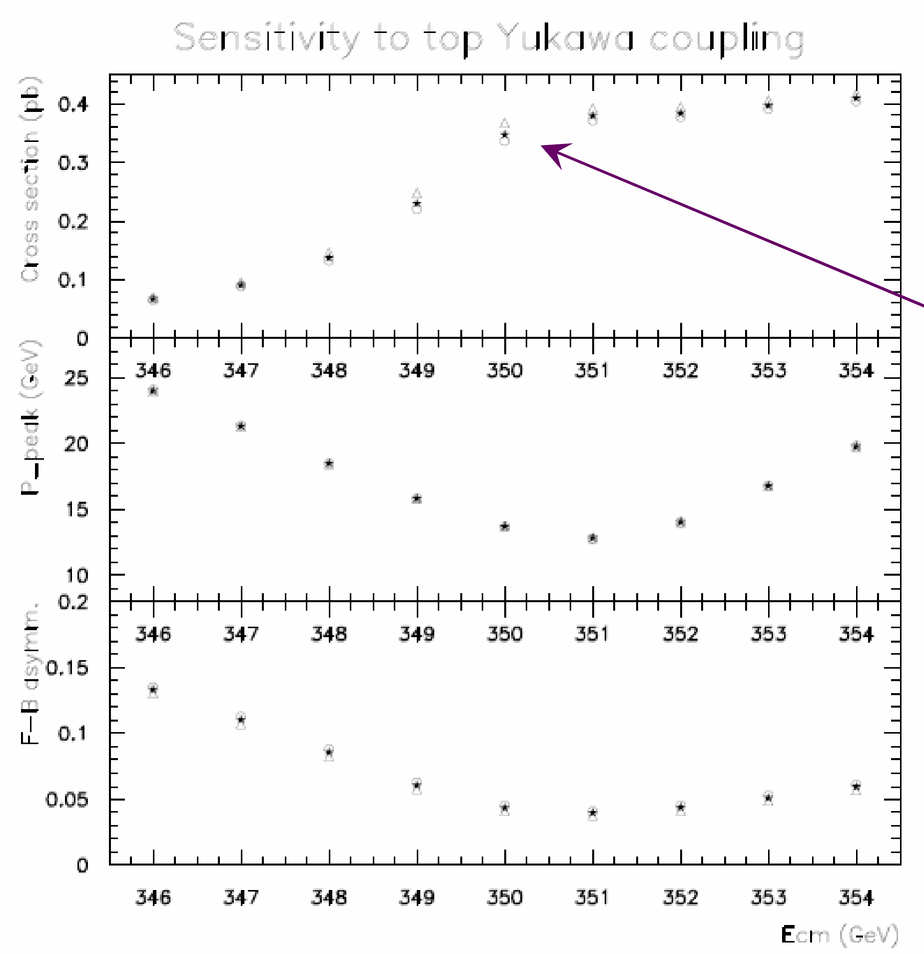


- LO (1-loop) shift: **+6%** (for $M_H = 120$ GeV) [Grzadkowski,Kuhn,Krawczyk,Stuart]
- NLO el.weak+QCD (2-loop): **+9%** [Eiras,Steinhauser]
- SM+SUSY NLO corrections: **~ 1%** (almost complete screening of SM effect)



[Kiyo,Steinhauser,Zerf]

Top quark Yukawa coupling



[Martinez,Miquel]

variation $\delta y_t = \pm 50\%$

- A measurement is challenging but not impossible
- Under optimistic assumptions: 30% accuracy is possible

Rare top quark decays

Rare top quark decays: FCNC

$$e^+e^- \to t\bar{t} \xrightarrow{\text{FCNC}} (Z/\gamma/g/h + j)(Wb)$$

Process	SM [67]	2HDM(FV) [67, 68]	2HDM(FC) [69]	MSSM [70]	RPV [71, 72]	RS [73, 74]
$t \to Zu$	7×10^{-17}	–	–	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	–
$t \to Zc$	1×10^{-14}	$\lesssim 10^{-6}$	$\lesssim 10^{-10}$	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	$\lesssim 10^{-5}$
$t \to gu$	4×10^{-14}	–	–	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	–
$t \to gc$	5×10^{-12}	$\lesssim 10^{-4}$	$\lesssim 10^{-8}$	$\lesssim 10^{-7}$	$\lesssim 10^{-6}$	$\lesssim 10^{-10}$
$t \to \gamma u$	4×10^{-16}	–	–	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$	–
$t \to \gamma c$	5×10^{-14}	$\lesssim 10^{-7}$	$\lesssim 10^{-9}$	$\lesssim 10^{-8}$	$\lesssim 10^{-9}$	$\lesssim 10^{-9}$
$t \to hu$	2×10^{-17}	6×10^{-6}	–	$\lesssim 10^{-5}$	$\lesssim 10^{-9}$	–
$t \to hc$	3×10^{-15}	2×10^{-3}	$\lesssim 10^{-5}$	$\lesssim 10^{-5}$	$\lesssim 10^{-9}$	$\lesssim 10^{-4}$

[Snowmass white paper]

- FCNC top quark decays are highly suppressed in the SM
  (light quark masses and small CKM angle)
- New Physics models introduce significantly higher rates

→ Any measured deviation from zero indicates NP in the top quark decay

Rare decays: FCNC

[Snowmass white paper]

LHC projections:

Process	Br Limit	Search	Dataset
$t \to Zq$	2.2×10^{-4}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	300 fb^{-1}, 14 TeV
$t \to Zq$	7×10^{-5}	ATLAS $t\bar{t} \to Wb + Zq \to \ell\nu b + \ell\ell q$	3000 fb^{-1}, 14 TeV
$t \to \gamma q$	8×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	300 fb^{-1}, 14 TeV
$t \to \gamma q$	2.5×10^{-5}	ATLAS $t\bar{t} \to Wb + \gamma q$	3000 fb^{-1}, 14 TeV
$t \to gu$	4×10^{-6}	ATLAS $qg \to t \to Wb$	300 fb^{-1}, 14 TeV
$t \to gu$	1×10^{-6}	ATLAS $qg \to t \to Wb$	3000 fb^{-1}, 14 TeV
$t \to gc$	1×10^{-5}	ATLAS $qg \to t \to Wb$	300 fb^{-1}, 14 TeV
$t \to gc$	4×10^{-6}	ATLAS $qg \to t \to Wb$	3000 fb^{-1}, 14 TeV
$t \to hq$	2×10^{-3}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	300 fb^{-1}, 14 TeV
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \ell\ell qX$	3000 fb^{-1}, 14 TeV
$t \to hq$	5×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	300 fb^{-1}, 14 TeV
$t \to hq$	2×10^{-4}	LHC $t\bar{t} \to Wb + hq \to \ell\nu b + \gamma\gamma q$	3000 fb^{-1}, 14 TeV

ILC projections:

Process	Br Limit	Search	Dataset
$t \to Zq$	$1.6\,(1.7) \times 10^{-3}$	ILC $t\bar{t}$, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 500 GeV
$t \to \gamma q$	1.0×10^{-4}	ILC $t\bar{t}$	500 fb^{-1}, 500 GeV

- Limits from 500 fb^{-1} ILC and 3000 fb^{-1} LHC are compatible
- Expect TLEP to perform even better, given the higher luminosity

Rare decays: single top

$$e^+e^- \xrightarrow[Z/\gamma\,\text{coupl.}]{\text{anomal.}} tq$$

- Studies are possible at E=250 GeV (maximal cross section) and at E=500 GeV (lower background)

[Aguilar-Saavedra,Riemann]
[Snowmass white paper]

Process	Br Limit	Search	Dataset
$t \to Zq$	$5\,(2) \times 10^{-4}$	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 250 GeV
$t \to Zq$	$1.5\,(1.1) \times 10^{-4\,(-5)}$	ILC single top, γ_μ $(\sigma_{\mu\nu})$	500 fb^{-1}, 500 GeV
$t \to \gamma q$	6×10^{-5}	ILC single top	500 fb^{-1}, 250 GeV
$t \to \gamma q$	6.4×10^{-6}	ILC single top	500 fb^{-1}, 500 GeV

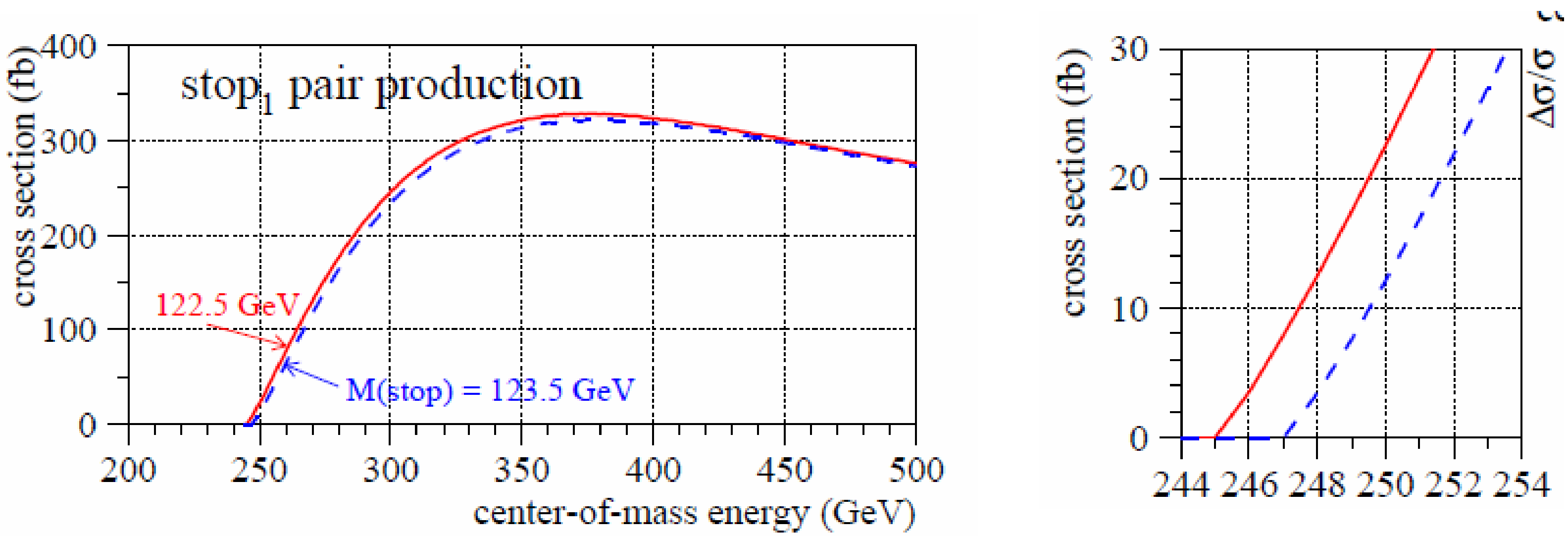
- Possibly stronger limits than from top quark pair production

- Opportunities below ttb threshold (E=240..250 GeV) are not well studied (above results rely on extrapolations)

Light stops

New Physics at around 350 GeV: light stops

- Heavy stop quark scenarios are mostly covered by LHC searches
- Light stops and compressed spectra are difficult, even for HL-LHC
- At lepton colliders: $e^+e^- \to \tilde{t}_1\,\tilde{t}_1^* \to c\tilde{\chi}_1^0\,\bar{c}\tilde{\chi}_1^0.$

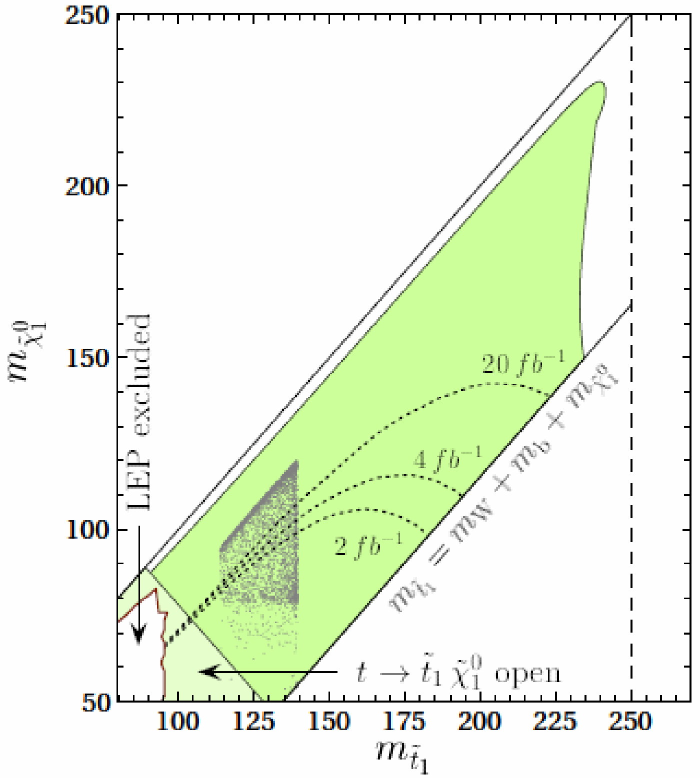


[Carena,Finch,Freitas,Milstene, Nowak,Sopczak]

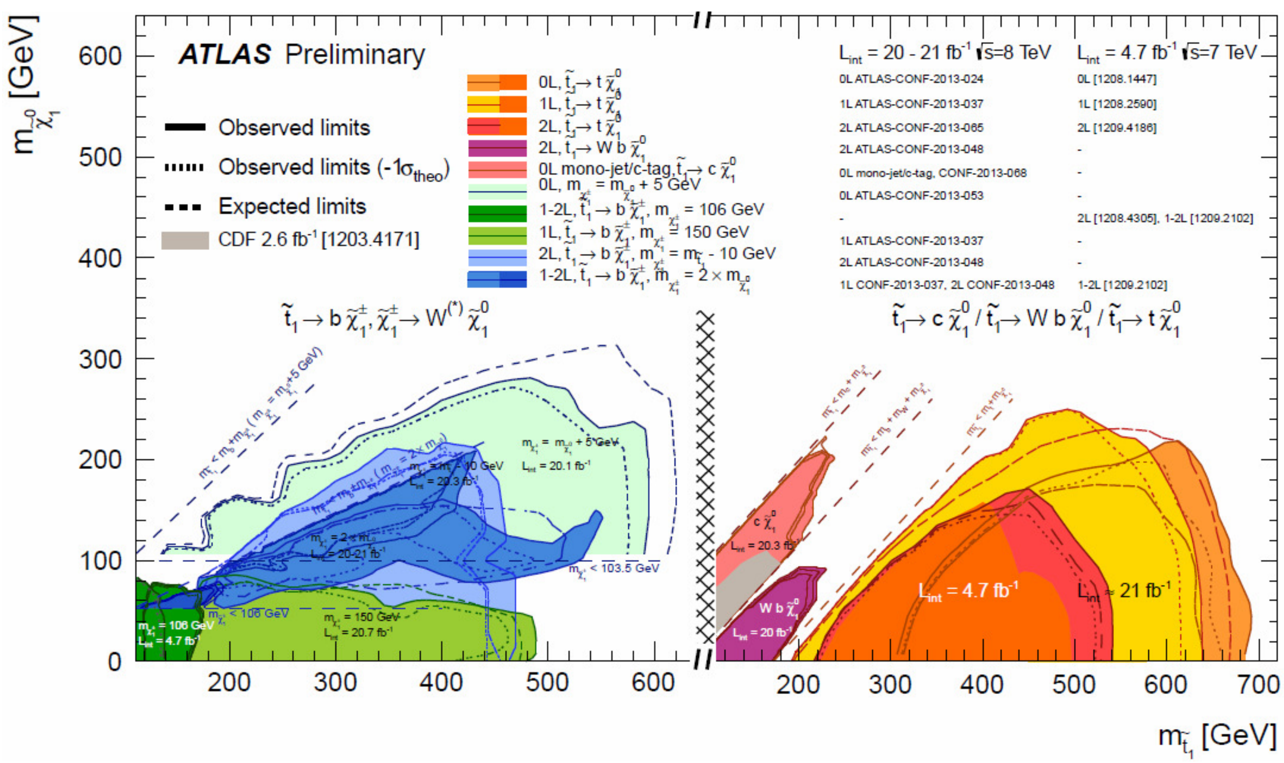
[Freitas,Milstene,Schmitt,Sopczak]

[Bartl,Eberl,Kraml,Majerottom,Porod,Spoczak]
[...many others...]

New Physics at around 350 GeV: light stops

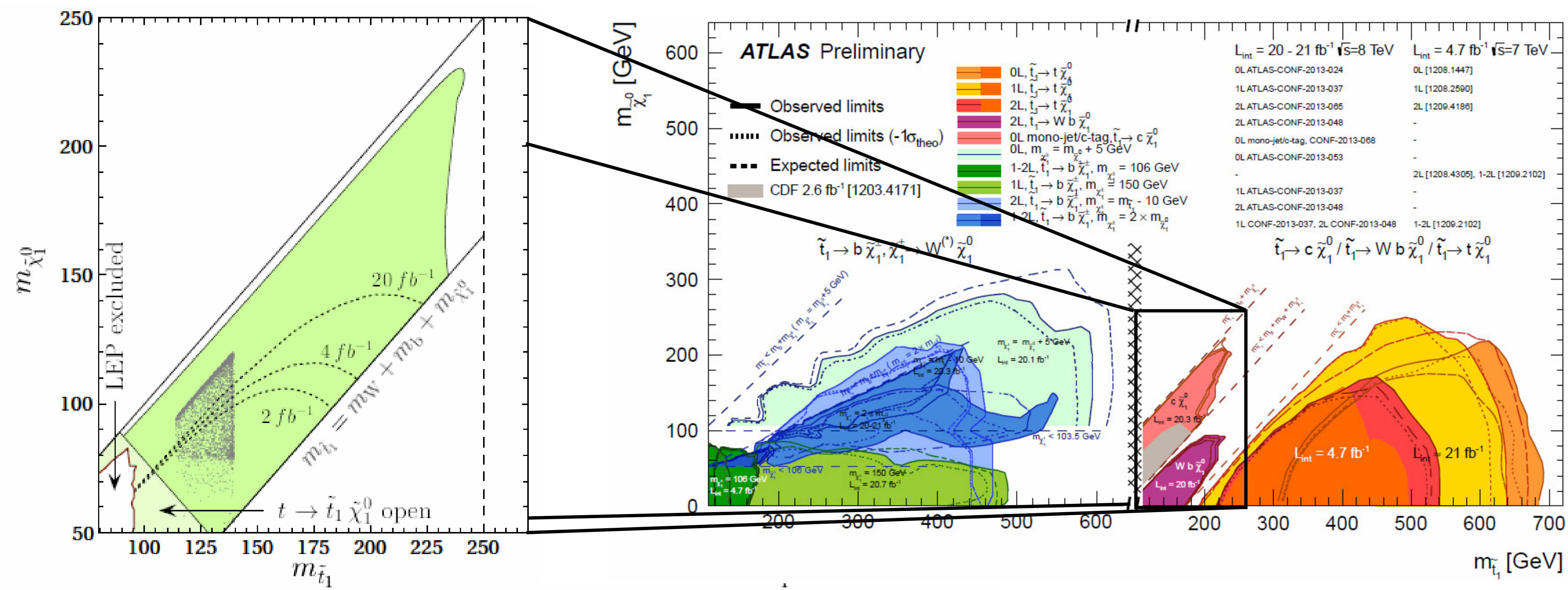


500 GeV ILC:
[Carena,Finch,Freitas,Milstene, Nowak,Sopczak]



7+8 TeV LHC:
[ATLAS at EPS 2013]

New Physics at around 350 GeV: light stops



500 GeV ILC:
[Carena,Finch,Freitas,Milstene, Nowak,Sopczak]

7+8 TeV LHC:
[ATLAS at EPS 2013]

SUMMARY: Top quark physics at LC

- Future NNNLO results will most likely reduce the theoretical uncertainty of the threshold cross section to ~ 3%.

- This level of accuracy is mandatory for precision top physics at threshold. It translates into an accuracy of 40-80 MeV on the top quark mass and about 2% on the top quark width.

- Realistic simulations incl. detector and beam effects, background,… do not compromise these conclusions.

- Precision on top quark electroweak couplings can be improved by an order of magnitude wrt. to LHC studies.

- Better than 20% accuracy on top quark Yukawa coupling is only possible at LC with $E \geq 500$ GeV.

- New Physics coupling to top quarks can be discovered in FCNC of the top quark decay and in single top processes.

Possible future studies

SUM at LC

- Future NNNLO results will most likely reduce the theoretical uncertainty of the threshold cross section to ~ 3%.

Realistic studies using TLEP energies and beam parameter

- This level of accuracy is mandatory for precision top physics at threshold. It translates into an accuracy of 40-80 MeV on the top quark mass and about 2% on the top quark width.

- Realistic simulations incl. detector and beam effects, background,… do not compromise these conclusions.

- Precision on top quark electroweak couplings can be improved by an order of magnitude wrt. to LHC studies.

- Better than 20% accuracy on top quark Yukawa coupling is only possible at LC with $E \geq 500$ GeV.

- New Physics coupling to top quarks can be discovered in FCNC of the top quark decay and in single top processes.

SUM at LC

Possible future studies

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TLEP allows studies of ttbar at 350 GeV *and* single top at 250GeV!

- Bett… s only poss…

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EXTRAS

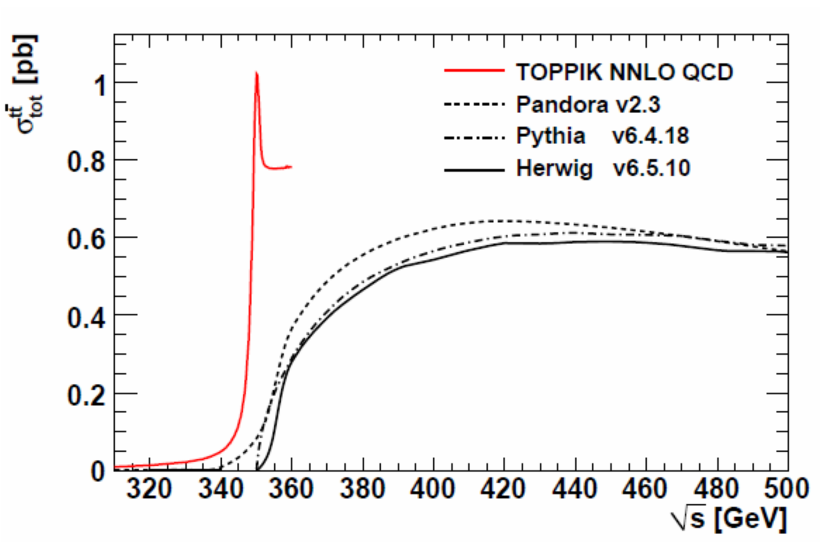
Simulation tools

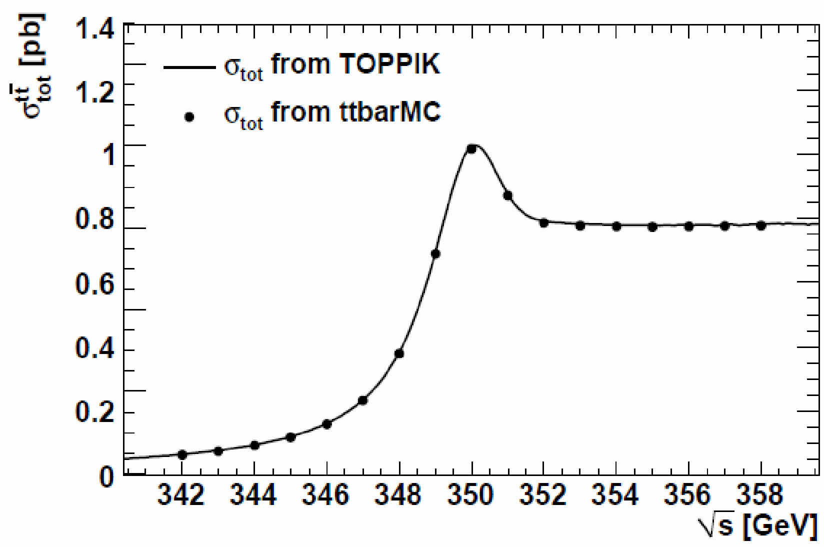
MC tools for threshold production beyond LO:

TOPPIK NNLO QCD [Hoang,Teubner]

ttbarMC NNLO QCD (based on TOPPIK) [Gournaris]

CALVIN: e+ e- → stops (NLO SUSY QCD + coulomb corrections) [Eberl,Bartl,Majerotto]





Extras

coupling	LHC, 300 fb^{-1}	e^+e^- [19]
$\Delta\widetilde{F}_{1V}^{\gamma}$	$^{+0.043}_{-0.041}$	$^{+0.047}_{-0.047}$, 200 fb^{-1}
$\Delta\widetilde{F}_{1A}^{\gamma}$	$^{+0.051}_{-0.048}$	$^{+0.011}_{-0.011}$, 100 fb^{-1}
$\Delta\widetilde{F}_{2V}^{\gamma}$	$^{+0.038}_{-0.035}$	$^{+0.038}_{-0.038}$, 200 fb^{-1}
$\Delta\widetilde{F}_{2A}^{\gamma}$	$^{+0.16}_{-0.17}$	$^{+0.014}_{-0.014}$, 100 fb^{-1}
$\Delta\widetilde{F}_{1V}^{Z}$	$^{+0.43}_{-0.83}$	$^{+0.012}_{-0.012}$, 200 fb^{-1}
$\Delta\widetilde{F}_{1A}^{Z}$	$^{+0.14}_{-0.14}$	$^{+0.013}_{-0.013}$, 100 fb^{-1}
$\Delta\widetilde{F}_{2V}^{Z}$	$^{+0.38}_{-0.50}$	$^{+0.009}_{-0.009}$, 200 fb^{-1}
$\Delta\widetilde{F}_{2A}^{Z}$	$^{+0.50}_{-0.51}$	$^{+0.052}_{-0.052}$, 100 fb^{-1}

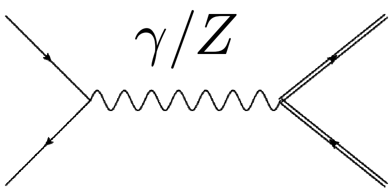
[American LC Working group]
[Baur,Juste,Orr,Rainwater]

Extras

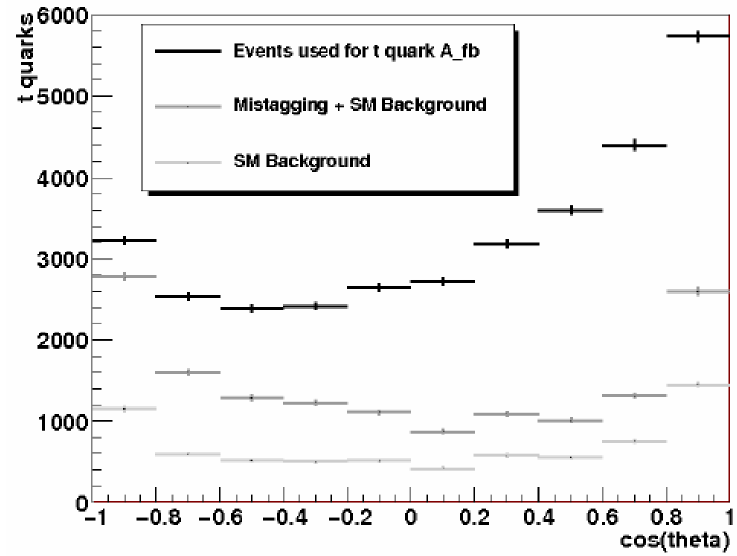
$$e^+e^- \to t\bar{t}$$

[Devetak,Nomerotski,Peskin] (2011)

Study A_{FB} with polarized beams to determine t-tb-Z couplings



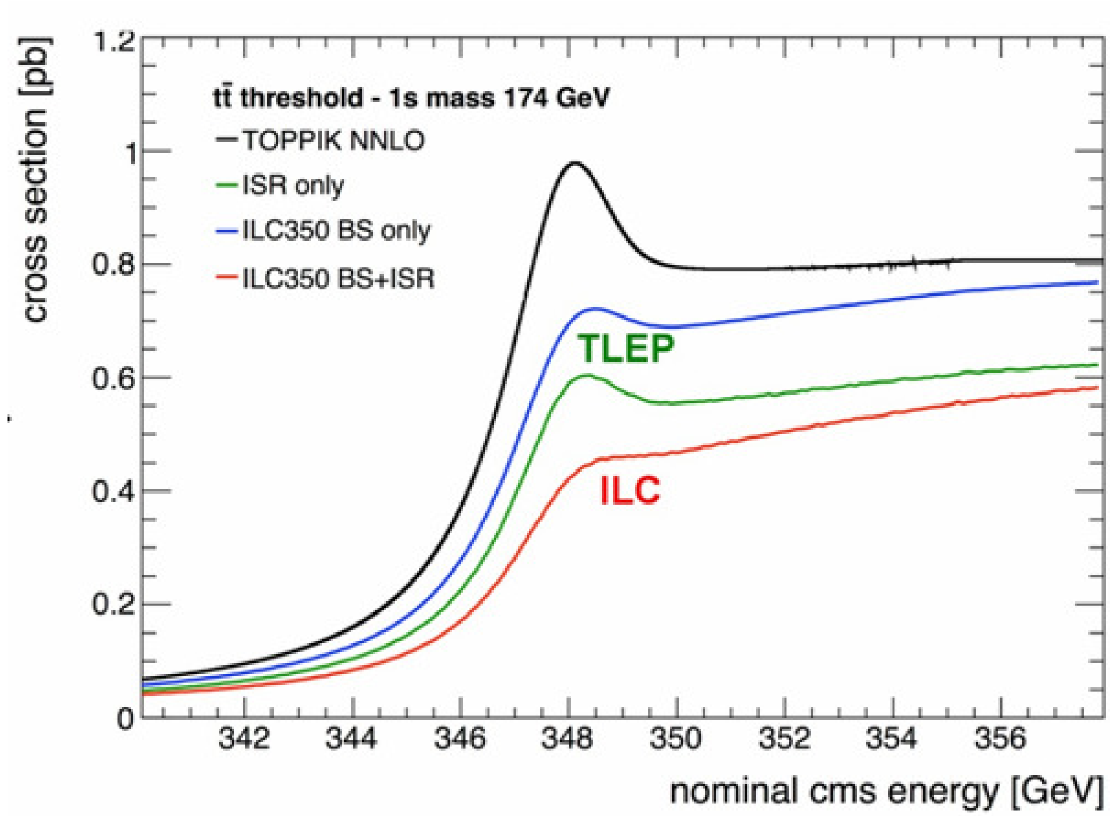
→ **LO asymmetry ~ 35%**



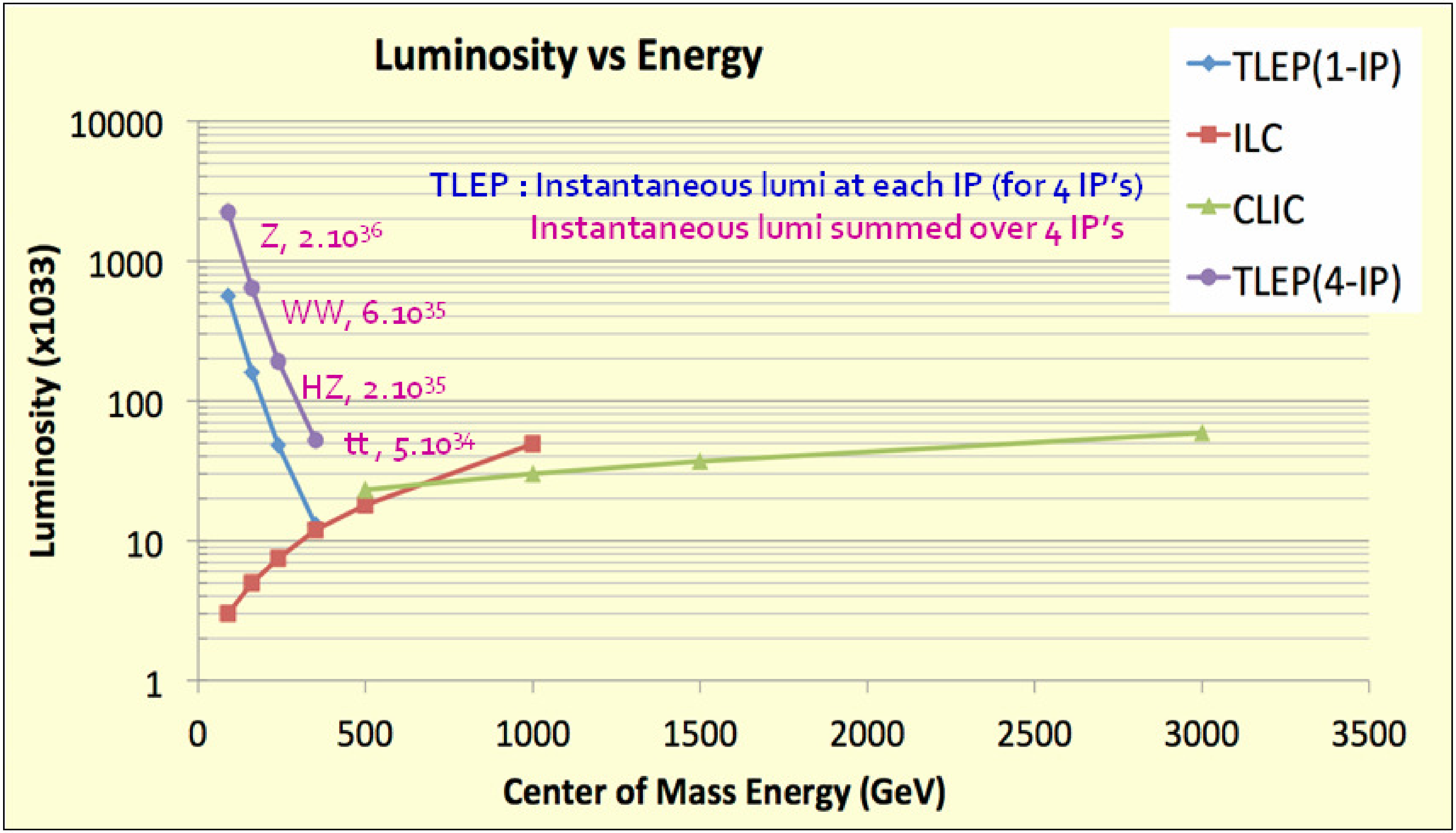
- 1% precision on A_{FB} is achievable in fully hadr. channel (requires two b-tags + b charge tagging)
- polarized beams at CM energy of 500 GeV and 500 fb^{-1}:

$$\delta F_{\mathrm{L}}^{Z} \approx 6\% \qquad \delta F_{\mathrm{R}}^{Z} \approx 12\%$$

allows to place strong limits on New Physics models



[Alan Blondel, snowmass talk]



[Alan Blondel, snowmass talk]

Extras

List of Known Corrections

- QCD Source of large theory uncertainty even today(NNNLO)
  - NNLO TopWGR(2000); Hoang-Teubner, Melnikov-Yelkhovsky, Penin-Pipovarov, Beneke-Signer-Smirnov, Yakovlev, Nagano-Ota-Sumino
  - NNNLO'/NNLL' Beneke-YK-Penin-Schuller(2008), Maquard-Piclum-Seidel-Steinhauser(2006)/Hoang-Manohar-Stewart-Teubner(2001), Pineda-Signer(2006)
- EW
  - EW 1-loop Grzadkowski-Kuhn-Krawczyk-Stuart(1987), Hoang-Reisser(2006)
  - Higgs/Z-gluon 2-loop Eiras-Steinhauser(2006)
  - W-gluon 2-loop vertex YK-Seidel-Steinhauser(2008)
  - unstable top effect(t -> bW) Hoang-Reisser-Femenia(2010)
- Susy/THDM
  - 1-loop Hollik-Schappacher(1999), Su-Wise(2001), YK-Steinhauser-Zerf(2009) /Denner-Guth-Kuhn(1992)

[Talk from Kiyo]